Defect-controlled ferromagnetism in the canonical ferromagnetic semiconductor (Ga,Mn)As

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Ferromagnetic semiconductors, in which magnetic ions incorporated into a host semiconductor lattice spontaneously align in a collectively ordered state mediated by free carriers, have become a topic of increasingly intense interest. In strong contrast to conventional metallic ferromagnets such as Fe, the low free carrier densities in semiconductors open up the possibility of "tuning" the magnetism by modulating the free carrier density either optically, electrically, or by co-doping. Such materials are hence critical to realizing semiconductor-based "spintronic" heterostructure devices that would integrate magnetic properties with conventional semiconductor functionality.

Although ferromagnetism has been observed in several classes of magnetic semiconductors, the "canonical" ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$ is of particular importance. $Ga_{1-x}Mn_xAs$ provides a model system in which a carrier-mediated ferromagnetism persists above $T = 100$ K, and recent studies consistently yield ferromagnetic transition temperatures (T_c) in the range 110 K < T_c < 172 K. A detailed theoretical and experimental understanding of ferromagnetism in $Ga_{1-x}Mn_xAs$ has been developing along several fronts. While it is recognized that the ferromagnetism in $Ga_{1-x}Mn_xAs$ originates from the Mn ions both acting as acceptors and providing a local moment, recent studies clearly indicate that point defects -- predominantly Mn interstitials (Mn_I) -- play a critical role in determining the physical behavior. Such defects compensate the substitutional Mn acceptors and in the case of Mn_I, may reduce the ferromagnetic moment through antiferromagnetic coupling to the substitutional Mn spins. Low temperature anneals have been shown to increase the carrier concentration and enhance T_c. This effect is particularly pronounced in thin epilayers with thicknesses of order 50 nm or less, in which T_c of up to 160 K has been obtained. Capping of these thin epilayers with a few monolayers of nonmagnetic GaAs significantly suppresses T_c in the as-grown samples and also reduces the physical changes induced by annealing. The effect on annealing increases with the capping layer thickness, and a 10 monolayer (ML) cap almost completely eliminates the effects of annealing. These results and data from time-dependent annealing studies at the University of Nottingham indicate that diffusion of defects to the free surface of $Ga_{1-x}Mn_xAs$ is an essential component of the effects of annealing, and they set important constraints on the eventual inclusion of $Ga_{1-x}Mn_xAs$ into heterostructure-based devices.

Most recently we have been exploring the exchange-biasing of this system by the growth of an antiferromagnetic layer on the top surface. This development and others indicate the promise of ferromagnetic semiconductors for device applications, although understanding how to control the physics of defects will be essential to implementing them effectively.

References: S. J. Potashnik *et al.*, Appl. Phys. Lett. **79**, 1495 (2001), Phys. Rev. B **66**, 012408 (2002) and Journal of Applied Physics **93** 6784 (2003); K.C. Ku *et al.*, Appl. Phys. Lett **82**, 2302 (2003); M. B. Stone *et al.*, Appl. Phys. Lett. **83**, 4568-70 (2003); N. Samarth *et al.*, Solid State Communications, **127**, 173 (2003); and K. Eid *et al.*, cond-mat-0312259 (Appl. Phys. Lett., in press).

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Figure 1. Low temperature MBE required for the growth of (Ga,Mn)As leads to a variety of defects including As antisites and Mn interstitials. This remains an important experimental system to investigate, however, since it can incorporate up to 10% Mn.

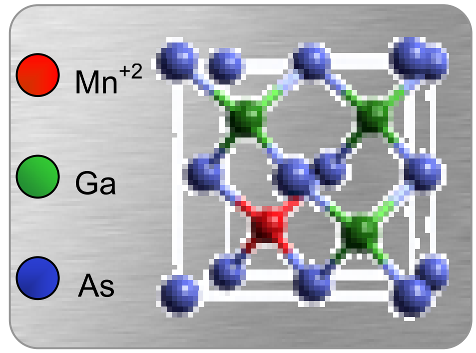

Figure 2. Point defects are an essential component of the physics of (Ga,Mn)As, and the magnetism can be altered significantly through annealing. These data show the temperature dependence of the magnetization of as-grown and annealed samples. The addition of a capping layer of a few monolayers of non-magnetic GaAs on the surface impedes the diffusion of Mn interstitials to the surface and thus eliminates the effects of annealing.